Longshore Sediment Transport and its Impact on the Coastal Zone of Karnataka, India: An Integrated Approach

Final-Synopsis submitted to

MANGALORE UNIVERSITY

for the award of

DOCTOR OF PHILOSOPHY

in

MARINE GEOLOGY

by

Mr. Ateeth Shetty
Research Scholar
Department of Marine Geology

Under the guidance of

Prof. K. S. Jayappa
Department of Marine Geology
Mangalore University
Mangalagangotri - 574 199
Karnataka, India

August, 2020

Final-Synopsis of the Ph.D. Work

Candidate Name	Mr. Ateeth Shetty
Research Guide	Prof. K. S. Jayappa
Department	Department of Marine Geology
Work place	Mangalore University, Mangalagangotri
Title of Research	Longshore Sediment Transport and its Impact on the Coastal Zone of Karnataka, India: An Integrated Approach
Date of Registration	01/01/2015
Registration Number	MU/EXB/Ph.D./CR.57/M.G./2016-17/E.13 dated 24/08/2016

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1. Introduction

Coastal zones are very important for human beings since time immemorial. More than half of the world population living on the coastal zone is found to be true in India also, with many sprawling and still growing coastal cities. Various developmental projects in the coastal zone or near the shoreline bring great pressure on it, leading to coastal hazard like erosion. Shoreline recession as a result of rising sea level has been recognized as a potential near future hazard by a number of countries. Long- and short-term shoreline changes are associated with various factors such as sediment supply, littoral transport, hydrodynamics of nearshore environment, and nature of coastal landforms (Scott, 2005; Kumar and Jayappa, 2009). Understanding the shoreline positions and erosion/accretion trend through time are of elemental importance to coastal scientists, engineers, and managers (Douglas and Crowell, 2000; Boak and Turner, 2005). Coastal erosion is a global problem affecting almost every country around the world having a coastline. This problem is expected to accelerate in the future due to global warming, which most likely will cause sea-level rise and increase the number of storm events across the globe. Decrease in rainfall has been attributed to reduction of sediment input to the beaches. Anthropogenic activities like construction of ports and harbors, sand and clay mining, construction of vented dams are also responsible for erosion, reduction in width of beaches and receding of shoreline.

Beach morphology is the widely used technique in reconstructing beach evolution trends (Delgado and Lloyd, 2004). Estimating eroded / accreted volume of sediment is possible from beach profiles (Cooper *et al.,* 2000). Beach profiles provide quantitative information for better understanding of spatio-temporal evolution (Ferreira *et al.,* 2012). Whereas, grain-size distribution has a fundamental relationship with the physical forces involved in the mechanism of transport and deposition of sediments. The spatial variations in grain-size trend contribute to sediment transport patterns (Poizot *et al.,* 2008). Assessment of vulnerability of a coast due to erosion is the prerequisite for coastal zone management authorities in proposing new coastal protective measures. Vulnerability assessment is a process of assessing the risk for formulation of strategies to reduce the risk arising from coastal erosion by proper planning and sustainable management. When natural processes affect human activities or infrastructure, the former becomes a natural hazard. Around the world, vulnerability maps are prepared for several coasts using remote sensing

and geographical information systems (GIS) techniques, multivariate analysis and numerical models (Cooper and McLaughlin, 1998; Dominguez *et al.,* 2005; Srinivasa Kumar *et al.,* 2010).

Variation of Suspended Sediment Concentration (SSC) and demarcation of littoral cells are useful to address the issues pertaining to coastal dynamics, sources, sinks and direction of littoral drift. Time series analyses of SSC data will provide quantity and behavior of sediment during different seasons in a particular area. Sediment-transport pathways and patterns of sediment accumulation in the littoral cell are not static, but change over geological, historical, and seasonal time scales. Some changes in the sediment budget are the result of natural cycles such as long-term changes in sea level, or of short-term fluctuations such as in wind and wave directions. Other changes in pathways and sinks in the sediment budget are the result of human influences, such as the construction of jetties/breakwaters/groins, or dredging practices. This information will be very useful for port and harbour authorities to reduce the cost of maintenance dredging. Understanding the coastal dynamics and longshore transport along the coastal zone of Karnataka would help in suggesting remedial measures for ongoing coastal erosion problem.

2. Study area

The study area stretches in three districts − Uttara Kannada, Udupi and Dakshina Kannada − of Karnataka State in the southern Indian peninsula. The coastal stretch is ~ 304 km from Talapady in the south to Devbagh in the north (12°45' − 15°00' N lat. & 74°00' − 75°00' E long.; Fig. 1) oriented in the NNW − SSE direction. The northern part is characterised by low energy coast with headlands, pocket beaches and the southern part is high energy coast with spits and straight sandy beaches. The later one is densely populated and experiences erosion of beaches and siltation of navigation channels of ports / harbours. Nine major river systems (Kali, Gangavali, Aghnashini, Sharavathi, Panchagangavali, Sita, Swarna, Netravati and Gurupur) originate in western slopes of the Western Ghats, flow westward and debouch in single or pair of two/three into the Arabian Sea. These rivers are the major source of sediment for beaches, but due to large scale sand mining from the estuaries / rivers and construction of about 250 vented dams across the rivers / streams resulted in the deficit of sediment input which in turn is responsible for erosion of beaches (Kumar *et al.,* 2010).

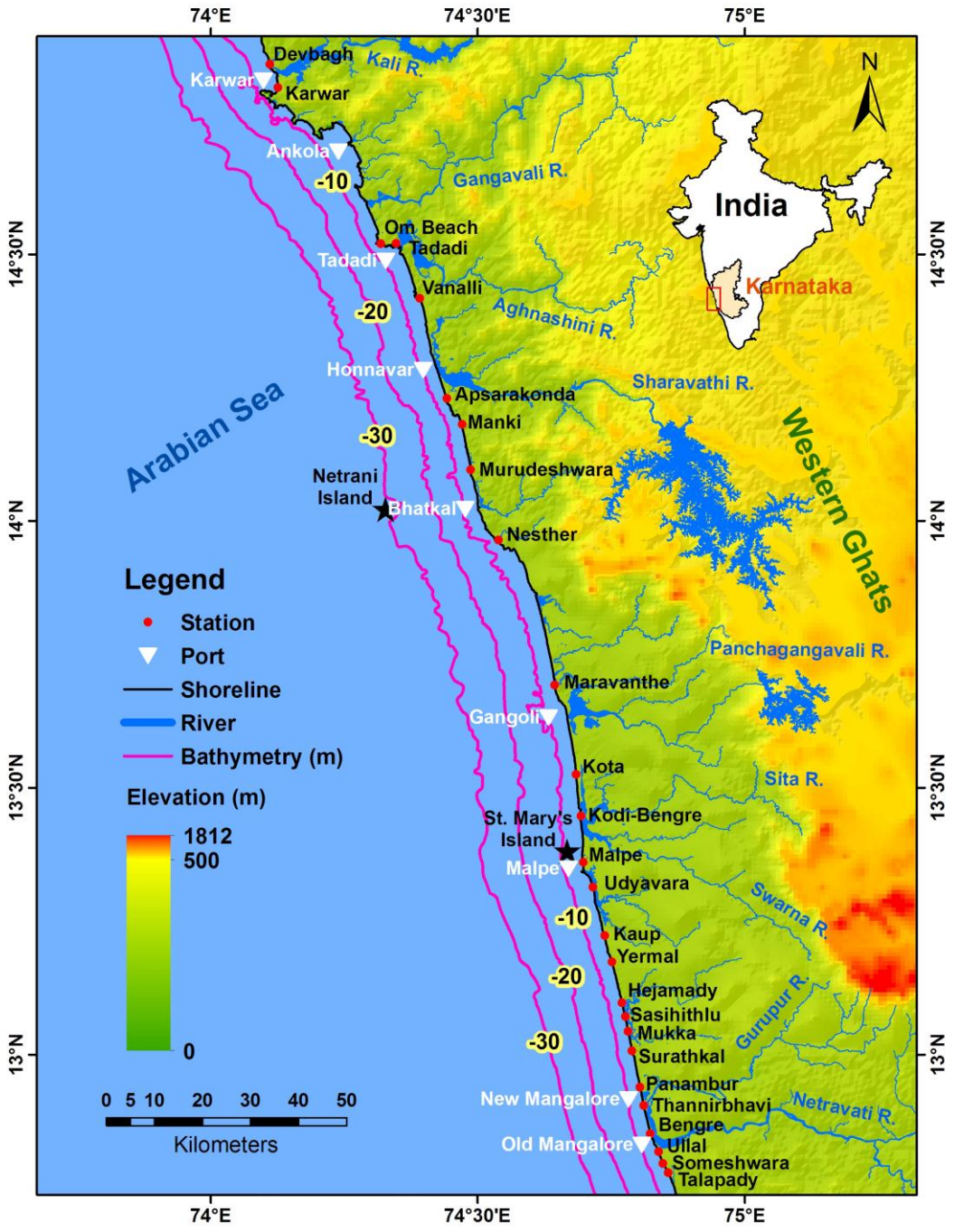

Fig. 1: Location map showing the 26 stations selected for the study, ports, shoreline, rivers, bathymetries and elevation along the Karnataka coast.

Majority of this coastline is protected with artificial structures such as seawalls, groins and breakwaters which intervene natural coastal processes. There are a few islands off the coast, the major ones being St. Mary's near Malpe and Netrani near Murudeshwara. The coastal belt experiences hot humid condition, south-west and north-east monsoons with

average annual rainfall of ~3,900 mm and temperature ranging from 17 to 34°C. Local community mainly depends on agriculture (paddy, coconut and areca nut), fishing (fresh and saline water), salt production from estuarine water, small to large-scale industries and tourism. This coastline is receiving increased attention due to industrial base like oil refinery, thermal power plant and ports. Due to extensive urbanisation and overexploitation of coastal environment, agriculture and fishery resources are drastically decreasing.

3. Aim and objectives

Aim of the present study is to investigate the impact of natural processes and anthropogenic activities on the coastal dynamics of the study area.

In order to fulfil the aim of the study, the major objectives taken-up are:

1. Investigation of beach morpho-dynamics.
2. To decipher the sediment characteristics, sources, physical conditions, and transport patterns.
3. To assess shoreline dynamics and coastal vulnerability index.
4. To estimate nearshore suspended sediment concentration and sediment trend.
5. To understand the impact of longshore sediment transport on coastal dynamics.

4. Organization of chapters

To achieve the above mentioned objectives, the whole thesis has been organized under eight chapters:

Chapter I: Introduction

The first chapter deals with a brief explanation on the importance of studying the coastal zone and the problems faced by the local community. Few important terms related to coastal zone are illustrated and discussed. National and international status of the research carried out on beach morpho-dynamics, sediment characteristics, sediment trend / transport patterns, coastal vulnerability, nearshore suspended sediment concentration, and longshore sediment transport studies is highlighted in this section along with the research gaps. The aim, objectives and significance of the present study area are emphasized at the end of this chapter.

Chapter II: Materials and methods

In order to fulfil the objectives of this study, the standard materials and methods followed are as detailed below, and the conceptual frame work of the methodology is shown in fig. 2.

- Seasonal beach profiling and littoral environmental observations at all the 26 selected stations using auto level technique, and estimating the erosion / accretion rate using Sands free software.
- Beach foreshore sediment sampling at all these 26 stations is carried out seasonally to decipher the sediment characteristics, sources, physical conditions, and transport patterns from sieve analysis data.
- Coastal vulnerability assessment to identify the erosion-prone areas by integrating thematic datasets such as shoreline dynamics, land-use / land-cover, geomorphology, geology, elevation and bathymetry using remote sensing and GIS techniques.

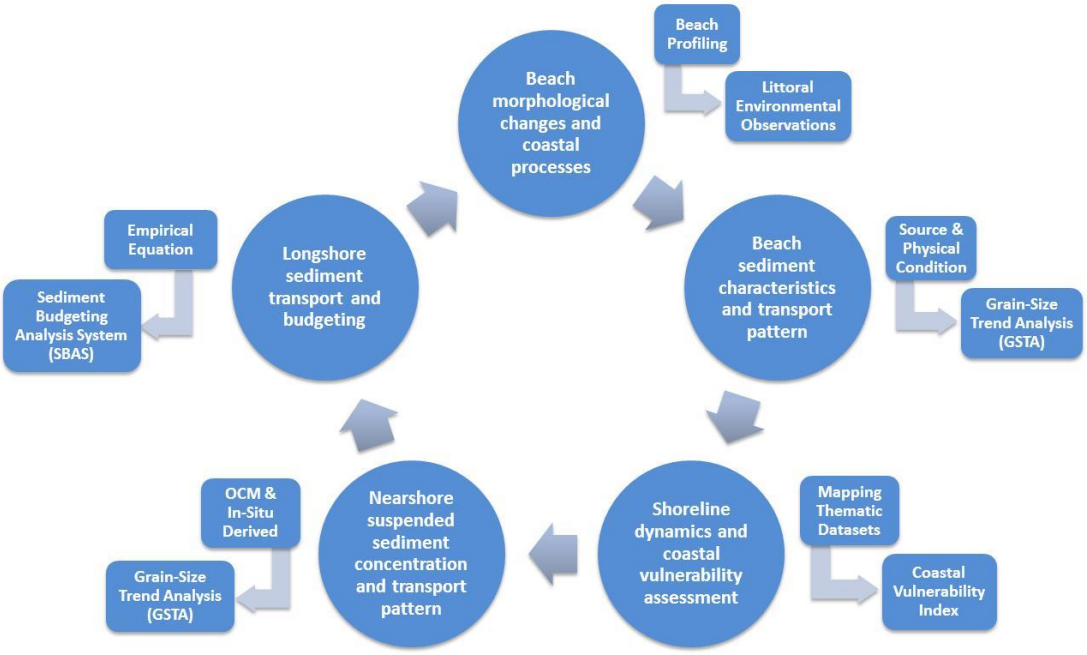
Beach Profiling
Littoral Environmental Observations
Beach morphological changes and coastal processes
Beach sediment characteristics and transport pattern
Source & Physical Condition
Grain-Size Trend Analysis (GSTA)
Shoreline dynamics and coastal vulnerability assessment
Mapping Thematic Datasets
Coastal Vulnerability Index
Nearshore suspended sediment concentration and transport pattern
OCM & In-Situ Derived
Grain-Size Trend Analysis (GSTA)
Longshore sediment transport and budgeting
Empirical Equation
Sediment Budgeting Analysis System (SBAS)

Fig. 2: Conceptual frame work of the methodology.

- Retrieval of SSC from Oceansat-II Ocean Colour Monitor (OCM) data and validation using in-situ sea truth SSC data obtained from nearshore water samples, and sediment trend was derived from bed sediment samples collected in estuaries and 5, 10, 15 m bathymetries at 13 selected transects.

- Estimation of longshore sediment transport rate using empirical equation and budgeting using Sediment Budgeting Analysis System software to understand the impact on coastal zone.

Chapter III: Beach morphological changes and coastal processes

This chapter deals with the seasonal (pre-monsoon, monsoon and post-monsoon) beach morpho-dynamics using cross-shore beach profiles monitored during pre-monsoon 2014 to pre-monsoon 2017, at twenty-six stations along the Karnataka coast. The field program involved beach profile surveys (Fig. 3) and littoral environment observations with the aim to examine the impact of natural processes and anthropogenic activities on the stability of beaches. Variation in cross sectional area (m^2) and volume (m^3) have been calculated using seasonal beach profile data for all the 26 stations. During pre-monsoon to monsoon moderate to very high erosion was noticed which is attributed to very high energy monsoon waves eroding the coast. Whereas, from monsoon to post-monsoon period low erosion to moderate accretion takes place due to moderate to low wave energy condition and from post-monsoon to pre-monsoon season moderate to high accretion was deciphered due to the favourable low wave energy. Large-scale erosion during SW monsoon is balanced during post-monsoon season but due to coastal structures, the ratio of sediment gain is reduced thus both natural processes and anthropogenic activities are attributed for beach erosion. Anthropogenic causes include dredging and construction of jetties, seawalls and groins. Complete understanding of coastal processes require basic knowledge of the foreshore slope, beach orientation, current direction-velocity, wave breaker height-direction-period, and surf zone width. This chapter emphasizes the need to observe beach changes over inter-annual periods before planning coastal protection measures.

Fig. 3: Showing beach profiling using automatic survey level.

Chapter IV: Beach sediment characteristics and transport pattern

This chapter deals with seasonal (pre-monsoon, monsoon and post-monsoon) sediment characteristics, sources, physical conditions, and transport patterns obtained from the analyses of sediment samples collected (Fig. 4) for three years at twenty-six stations along the tropical beaches of the eastern Arabian Sea. The sediments are medium to coarse in size and moderately to poorly sorted during the south-west monsoon attributable to high wave energy and strong winnowing action. During pre- and post-monsoon seasons the sediments are medium to fine and are very well to moderately sorted which signifies low to moderate energy condition. The linear discriminate function indicates that the sediments are mainly deposited in the beach or the shallow marine environment under the influence of turbidity current. Beach or tractive current energy conditions and rolling, bottom suspension & rolling including graded suspension & no rolling mechanics of transportation are inferred from CM diagrams. The sediment transport patterns reveal that the direction in most of the stations is towards the south. Due to seasonal variation in climate, the study on sediment transport trend is an important pre-requisite for beach erosion management, planning, design of beach nourishment and hard protective structures in a coastal environment.

Fig. 4: Image showing beach sediment sampling.

Chapter V: Shoreline dynamics and coastal vulnerability assessment

This chapter deals with the coastal vulnerability assessment along Karnataka, south-west coast of India to identify the erosion-prone areas by integrating thematic datasets such as shoreline dynamics, land-use / land-cover, geomorphology, geology, elevation and bathymetry using remote sensing and GIS techniques. Based on littoral cell concept, the 304

km coastline of Karnataka is divided into fourteen littoral cells and each cell into a number of transects at uniform intervals. Along this coastal stretch, ~265 km (87%) is vulnerable to erosion of which ~179.5 km (59%) is undergoing erosion at various magnitudes (Fig. 5). Littoral cells in the south are subjected to high erosion and vulnerable, whereas the beaches having human interventions are the most erosion-prone. This approach provides valuable information on the degree of potential vulnerability risk which serves as a guide to develop adaptation measures by the coastal zone management authority.

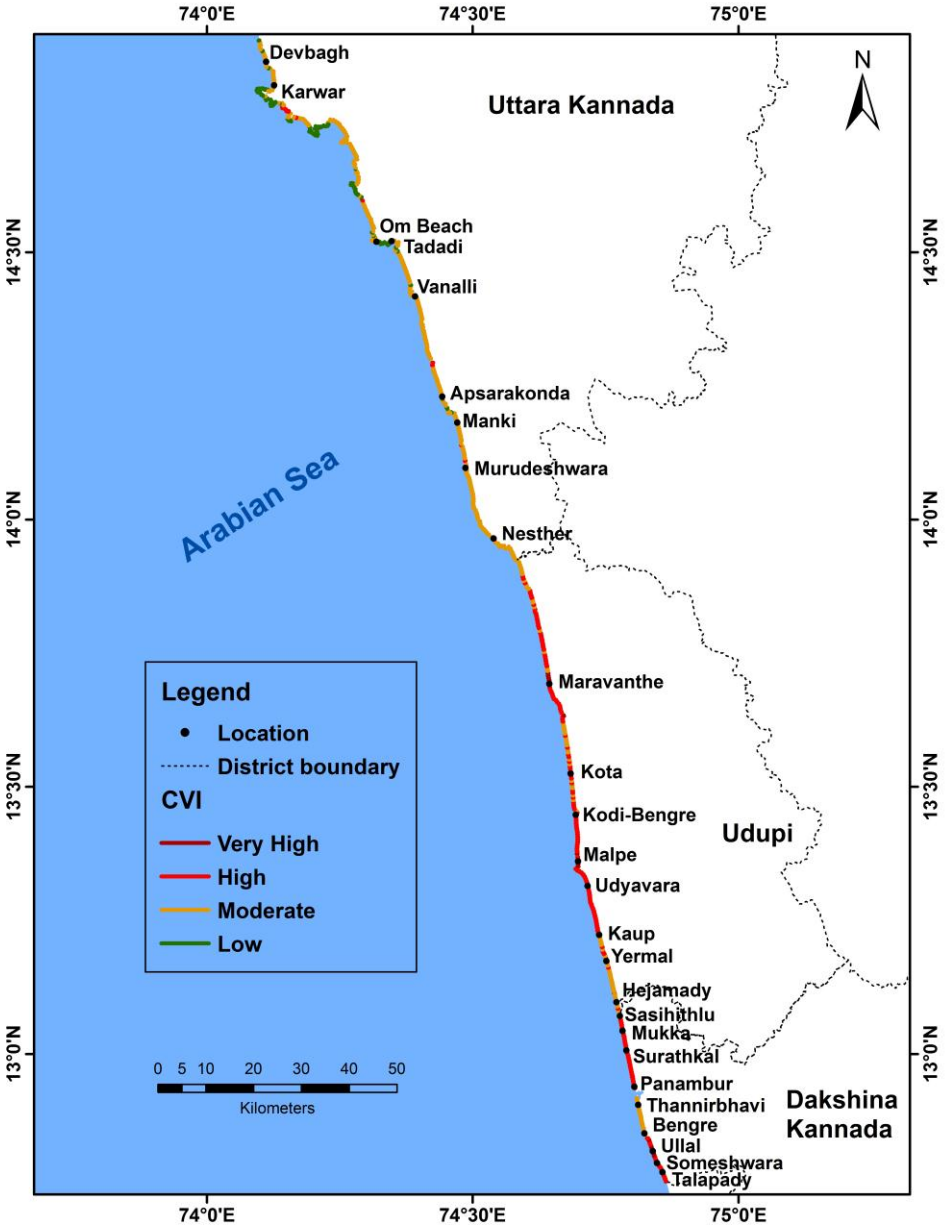

Fig. 5: Showing vulnerability along the Karnataka coast.

Chapter VI: Nearshore suspended sediment concentration and transport pattern

In this chapter, the suspended sediment concentration (SSC) was derived using Oceansat-II OCM satellite images to understand the coastal dynamics and regional sediment transport in nearshore waters. The geo-rectified images were atmospherically corrected and SSC values were derived from the water leaving radiances using an algorithm proposed by Tassan (1994) and later undergone site specific modification by Avinash *et al.* (2012) and Ratheesh *et al.* (2012). SSC was derived from shoreline to 20 m depth for thirteen transects selected between Talapady and Malpe during January, February, November and December months from 2014 to 2017 (Fig. 6). OCM and in-situ derived SSC (water samples collected in estuaries and nearshore (at 5, 10 and 15 m bathymetries) are compared for January and November 2016 for validation of satellite data. High concentration in the southern side of the study area is due to high wave activity, sediment discharge from river, dredging activity of New Mangalore Port, and construction of offshore reefs at Ullal. In-situ samples show high concentration in the bottom waters in estuaries which signify the dominance of bed load transport than suspended load. In nearshore waters, high concentration in the surface, mid and bottom waters is observed along the stations impacted by anthropogenic activities. The suspended sediment concentration estimated in case-2 waters based on ocean colour data and in-situ data is observed to be positively correlating (± 10 mg/l). SSC values deciphered using regional algorithm provides accurate estimates in coastal waters off south-west India. Sediment transport pattern derived from statistical parameters of bed sediment samples collected in estuaries, 5, 10 and 15 m depth during January and November 2016 showed offshore, southward and northward directions. Natural and anthropogenic structures act as barriers for coastal sediment transport. The direction of sediment transport pattern in the coastal waters helps in maintenance of navigational channels and planning the coastal structures in management of coastal zone. The study reveals that sediment dynamics are primarily controlled by currents and the river input. Satellite-derived SSC data have been found useful for Indian coasts because of their high spatial, spectral and temporal resolutions. This chapter outlines the applications of state-of-the-art operational Indian Remote Sensing satellite Oceansat-II data in understanding the dynamics of sediment transport.

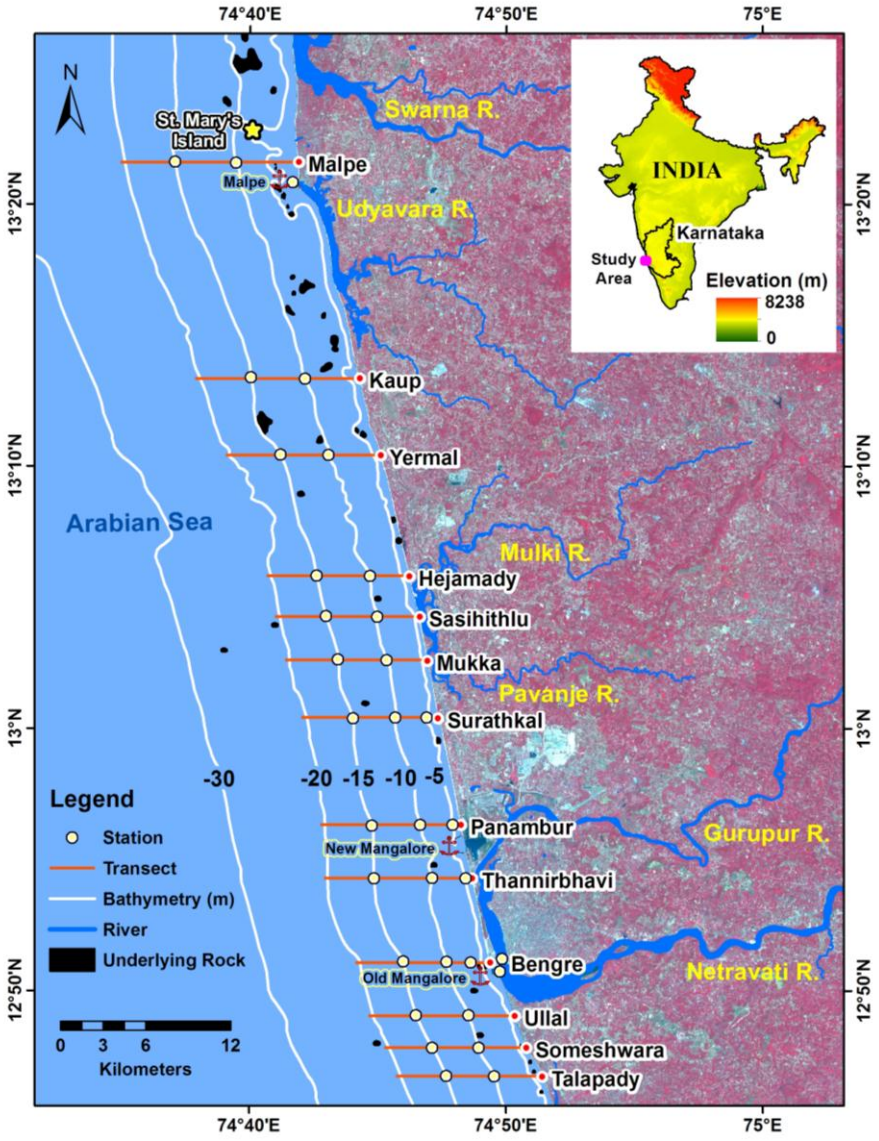

Fig. 6: Showing thirteen transects from shore to 20 meter bathymetric contour as well as water and sediment sampling stations.

Chapter VII: Longshore sediment transport and budgeting

In this chapter, longshore sediment transport rate is estimated and sediment budget is carried out using emphirical equations. The beach orientation, nearshore slope, median sediment size, significant wave height, wave direction and peak wave period are used in the estimation of longshore sediment transport rate using Kamphuis (1991) formulae at all the 26 stations (Fig. 7a). The nearshore wave parameters - significant wave height, wave direction and peak wave period derived using the XBeach numerical model (Roelvink *et al.* 2010). Bathymetric grid (Fig. 7b) was generated from naval hydrographic chart (NHO,

2004; 2005) and WaveWatch III global wave model data at 0.5° interval (https://pae-paha.pacioos.hawaii.edu/erddap/griddap/ww3_global.html) for a period of four years (Jan 2014 to Dec 2017) were used as an input to the numerical model and the model results were validated with the measured wave rider buoy data obtained from Indian National Centre for Ocean Information Services (https://www.incois.gov.in/portal/datainfo/wrb.jsp). The sediment budget is a tally of sediment gain and loss within a specified littoral cell, or in a series of connecting cells. Sediment Budget Analysis System (SBAS) is a graphic-based interface to solve sediment budget for each littoral cell with sources, sinks, volume changes, placement and removal volumes into and out of cell (Rosati and Kraus, 2003). SBAS quantifies the natural sediment transport processes and anthropogenic activities.

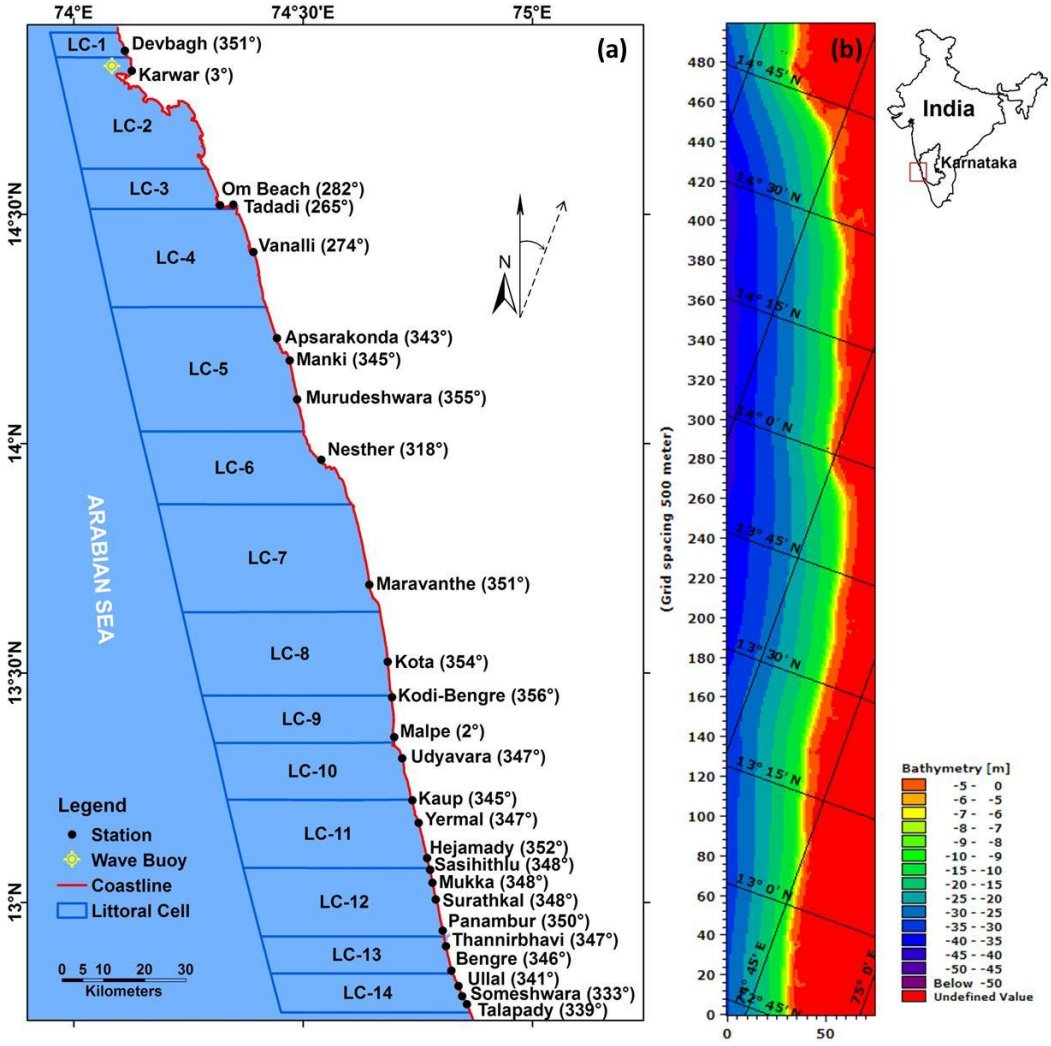

Fig. 7: Showing fourteen littoral cells and twenty-six selected stations with beach orientation and, (b) bathymetric grid used in the XBeach model.

Chapter VIII: Conclusion

In this chapter, the major findings drawn from each chapter is highlighted. The results of beach morphological changes revealed that during pre-monsoon to monsoon moderate to very high erosion attributed to very high energy monsoon waves eroding the coast. Large-scale erosion during SW monsoon was balanced during post-monsoon season but, due to anthropogenic activities (dredging, and construction of coastal structures) the ratio of sediment gain was reduced. Thus both natural processes and anthropogenic activities were attributed to erosion.

From the results of sediment textural parameters, the Karnataka coast can be broadly divided into high energy beaches with steep slopes consisting of medium to very coarse sand, moderate energy beaches with moderate slope and fine to medium sand, and low energy beaches with gentle slope and fine to very fine sand. The results obtained from the grain-size trend analysis reveal that the sediment transport direction in most of the stations along the Karnataka coast is towards south. This aspect needs to be considered while designing the orientation of breakwaters in order to minimize littoral drift entering into navigation channels of ports/harbors.

Vulnerability of the Karnataka coast mainly depends on the shoreline dynamics, land-use / land-cover, geomorphology, geology, elevation and bathymetry. On the basis of shoreline dynamics, the Karnataka coast is classified into erosion and accretion zones. Coastal vulnerability along the Karnataka coast is classified into very highly vulnerable, highly vulnerable, moderately vulnerable, and low vulnerable zones. Littoral cells on the north are subjected to moderate vulnerability, whereas on the south are highly vulnerable. Therefore, it is very much necessary to take up adaptation strategies in advance which serve as an indicator of the threats to people living in coastal zones. The study conclusively proves the application of RS data and GIS technologies for better planning in order to mitigate the losses due to erosion.

Monitoring and understanding the sediment dynamics and suspended sediment transport is an important issue for coastal engineering related activities. Study on transport mechanism of suspended sediments in the marine environment is essential not only to safeguard of marine installations or navigational channels, but also for the coastal structure design, environmental protection and disaster reduction. The high SSC during pre- and post-

monsoon seasons along the stations in the southern side of the study area is attributed mainly to the anthropogenic activities. Satellite-derived SSC data have been found to be useful in understanding the nearshore suspended sediment concentration and transport pattern due to their high spatial, spectral and temporal resolutions.

Direction of longshore sediment transport depends on the direction of incoming waves with respect to shoreline which in turn determines the direction of the longshore current. It is found that during the pre- and post-monsoon periods, the sediment transport was towards south, and during monsoon it was northward. It is clearly observed that during the monsoon season the variation of longshore sediment transport rate dependent on the breaker height and angle. The net longshore sediment transport rate along the Karnataka coast was found to be southwards (-647,406 m^3/annum) and sediment budget showed loss of -67,200 m^3/ annum. Changes in the sediment budget are the result of natural changes in wave characteristics. Changes in pathways and sinks in the sediment budget are the result of human influences, such as construction of jetties/breakwaters/groins, or dredging practices. Understanding the coastal dynamics and longshore sediment transport along the coastal zone of Karnataka would help in suggesting remedial measures for ongoing coastal erosion problem.

Recommendations for using advanced instruments and modeling techniques for similar studies in the future include: beach morphological studies using advanced instruments like RTK-GPS having horizontal and vertical accuracies of <±5 cm. Nearshore measurements of wave, tide, current and suspended sediment concentration by mooring oceanographic instruments like wave buoy, tide gauge, current meter and optical backscatter sensor. Numerical modeling of morphological changes, sediment transport rates and shoreline changes.

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Signature of the Candidate
(Mr. Ateeth Shetty)

Signature of the Research Guide
(Dr. K. S. Jayappa)